

A constant-frequency machine with a varying/variable speed

## TECHNICAL FIELD

5 The present invention relates to an electric rotating  
alternating current (ac) machine, which in its basic  
design comprises a main machine and a regulating machine  
with a common mechanical shaft and a converter which  
10 rotates with the shaft and which permits brushless control  
of the machine. The main machine is provided with a stator  
winding connected to a distribution or transmission power  
network for medium or high voltage, that is, for 1 kV and  
up to higher voltages.

15 The invention comprises a method when using the converter  
rotating with the shaft.

The machine may be used for conversion of mechanical power  
into electric power and for conversion of electric power  
20 into mechanical power, respectively. This means that the  
machine may function both as a generator and as a motor.  
In connection with the conversion, both the active and the  
reactive power, which is associated with the actual opera-  
tion, may be controlled.

25 During generator operation, the frequency of the voltage  
generated by the stator winding may be maintained con-  
stantly equal to the mains frequency at varying speed of  
the machine.

30 During motor operation, the stator winding is connected to  
a power network. Operation with varying speed is con-  
trolled in a brushless manner by way of the regulating  
machine and the converter rotating with the shaft.

35 The invention has its primary field of application at  
large machine powers. As far as generator drives is

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concerned, typical applications lie within the range of 3-300 MW. Motor drives of up to 100 MW and higher may be manufactured. Machine powers both below and above the power ranges mentioned may be advantageously used.

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The machine may be used in connection with hydroelectric machines, pump power plants, wind power plants, gas and steam turbines and as reactive-power compensator, power flow controller and transmission link in connection with power networks, as well as drive source for various motor drives.

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The described embodiments of the invention and the description of the background art show so-called radial flow machines. The machine may also wholly or partly be designed with one or more axial flow machines.

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As regards machines for generation of electric power, there are a plurality of accepted terms such as electric generator, electric-power generator, hydroelectric generator, etc. In this description, these "generators" will be referred to as "electric generators", unless it is necessary from the context to specify this term more precisely.

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#### BACKGROUND ART

Generally, ac machines may be used both for generator operation and motor operation, but the optimal embodiments differ somewhat. Thus, there is a "background art" which is specific to both operating modes.

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During generator operation, the task of the machine is to generate electric power. To be able to do this, the electric generator is driven by a drive means, whereby mechanical power is transformed into electric power. Since generation of electric power is normally associated with

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power networks, specific requirements are made for maintaining both voltage and frequency constant as well as for controlling both active and reactive power. The following description of the background art, as far as generator operation is concerned, will consequently to a large extent deal with how to achieve the desired performance relating to these parameters.

When an ac machine is used in a motor drive, electric power is converted into mechanical power where the conversion to an increasing extent is associated with speed control of the output shaft, that is, of the speed of the machine. This is particularly true of the present invention. Consequently, the description of the background art as far as motor drives are concerned will substantially deal with speed-controlled motor drives. Motor drives primarily relate to control of torque and speed of an output shaft. However, in the same way as generation, motor drives are also associated with control of both active and reactive power.

A significant problem area as regards motor drives with ac machines is their start, that is, the start-up from zero speed to the relevant control range around synchronous speed. The description of the background art will also comprise a description of the existing start-up methods to be able to prove the improved start-up methods which are available when using ac machines according to the invention.

As described under the "TECHNICAL FIELD", the invention will comprise a converter. The description of the background art both as regards generator drives and motor drives will therefore substantially refer to embodiments where converters are included. From an electrical point of view, the converters in question will be described

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with the aid of accepted basic symbols according to Figure 1, which clearly describe their function, that is, according to

5 Figure 1a which describes ac-to-dc conversion; according to

Figure 1b which describes dc-to-ac conversion; according to

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Figure 1c which describes ac-to-ac conversion; and according to

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Figure 1d which describes conversion from one dc voltage to another dc voltage.

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The ac-to-ac converters which will be used for carrying out the invention are referred to, in accordance with English terminology, as "ac-to-ac bidirectional converters" and are explained in Webster's Electrical Engineering Handbook, Wiley 1999, under the sections AC-AC POWER CONVERTERS, written by Rik W. De Doncker, Aachen University of Technology. The concept ac-to-ac converter means in this connection conversion of frequency and/or amplitude.

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Converter connections for large powers are currently designed mostly with silicon-based thyristors. These connections often require large reactive powers because the currents of the ac network experience a considerable phase shift relative to the voltages thereof. This implies that the dimensioning of machines for converter-based systems and of converters must take into consideration reactive power flows, that is, reactive losses in the reactances of the machines and of ac networks as well

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as the need of power factor correction, thus not only the

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purely active power flows with more or less negligible active losses.

From a mechanical point of view, according to the state of the art, converters which will be used in connections relating to electric machines are normally constructed as units which are placed adjacent to the machine or fixedly mounted on the stator of the machine. During the last few decades, there has been a successive shift towards mounting converters fixedly on the rotating parts, that is, in or on the rotating part, for example as parts of a rotating brushless system for dc excitation of synchronous machines according to the below. In certain contexts, converter-controlled rotor resistors are also used.

One converter connection which is very important in the above-mentioned context is a connection according to Figure 1c, that is, a connection which relates to frequency or ac-to-ac conversion. The mode of operation of an ac-to-ac converter may be achieved in several different ways. One fundamental way is for the conversion to be performed by means of ac-dc-ac conversion, that is, with an intermediate dc link. Another way is for the conversion to be achieved by means of ac-to-ac conversion which may take place in various embodiments. Examples of such are conversion by means of so-called cycloconverters with line-commutated double converters or with so-called matrix converters with self-commutated bidirectional power semiconductor.

Since in this connection only the main functions as energy converters are of interest, a detailed description and control, protection etc. of converters as well as communication of signals to and from rotating parts will not be dealt with in this description.

Both with regard to generator operation and motor operation of ac machines, the well-known term synchronous speed occurs. There is an unambiguous relationship between the speed of rotation ( $n_r$ , r/min) of the rotor, the number of poles ( $p$ ) of the machine, and the frequency ( $f_s$ , Hz) of the voltage of the machine. The relationship during synchronous operation is normally described as

$$n_r = (2/p) \cdot f_s \cdot 60 \quad (1)$$

The immediately following part of the background art will deal with the use of ac machines as electric generators.

The starting-point is an electricity-generating unit in the form of an electric generator and a drive means, mechanically connected thereto, in the form of a turbine, a drive motor of some kind, or the like. For the electric generator to be connected to a power network and contribute to the electricity supply of the power network, it is required that the voltage of the electric generator, possibly via a transformer, should be adapted to the voltage of the power network and that the frequency of the voltage should correspond to the frequency of the power network.

To achieve the desired and constant frequency, it is thus required that, with a given number of poles, the unit rotates at a constant speed, which implies that the drive means must have some form of control equipment for different load conditions, etc. A varying water flow, head and network oscillations require both static and dynamic accuracy of the frequency control of the hydroelectric generator.

To begin with, a short description of how the magnetization systems for electric generators rotating at a "constant" speed are designed according to current

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technique will be given. This is done partially by means of so-called brushless magnetization with the aid of an exciter and converter rotating with the shaft.

5 One example of a design of a brushless exciter is described in the ABB pamphlet "Brushless exciter, SEGEN/HM 8-001. It is clear from the pamphlet that the exciter is an ac machine, the stator of which is provided with salient poles and the rotor of which has a three-phase ac  
10 winding for feeding the above-mentioned converter, preferably a six-pulse converter bridge. The direct voltage, dc, of the converter is connected to the field winding of the electric generator. The voltage control of the electric generator takes place by influencing the  
15 magnetization of the exciter via its stator winding (field winding). Thus, having a converter, rotating with the shaft, for ac-to-dc conversion and dc excitation of the pole system of electric generators with a "constant" speed is known technique.

20 Figure 2 shows, in principle, how a brushless exciter is used in conventional electric generators, that is, with voltages up to 25 kV. The figure shows a vertical-shaft electric generator 1 which, on the common shaft 2, is  
25 arranged with the rotor of the electric generator with a winding 3, the rotating ac winding 4 of the exciter, a converter 5 rotating with the shaft, and a drive means in the form of a turbine 6. The stator 7 of the electric generator is connected to a high-voltage network via a  
30 step-up transformer 8. Figure 2 also shows the stationary field winding 9 of the exciter. Figure 3 shows the corresponding embodiment of the magnetization system in which the electric generator is designed as a high-voltage generator according to WO 97/45919. No transformer for  
35 connection to a high-voltage network is then needed. Otherwise, the reference numerals are the same as in Figure 2. Figure 4 shows the corresponding embodiment of

the magnetization system where the electric generator according to WO 976/45907 is designed as a 2x3-phase high-voltage generator for supplying an HVDC installation 10 with a 12-pulse connection. The reference numerals are otherwise the same as in Figure 2.

A special embodiment of dc excitation of an electric machine rotating at constant speed is described in PCT/EP98/007744, for "Power flow control" in a trans- mission line. The stator windings of the electric machine are here connected in series with the conductor of the transmission line without a connected neutral point. The rotor of the electric machine is provided with two/three dc rotor windings, displaced 90/120 electrical degrees, 15 for control of amplitude and phase of the voltage of the electric machine. Supply of the rotor windings occurs via a magnetizing exciter rotating with the shaft and a converter/ac-to-dc converter for each one of the rotor windings.

20 According to IEC 34-1/2, normalized permissible frequency and voltage deviations exist for electric generators. To manage the apparent rated power of the electric generator, the working point of the electric generator shall 25 lie within a so-called A-zone which (largely) is limited by +/- 2% as far as frequency is concerned and +/- 5% as far as voltage is concerned. However, the working point is allowed to lie within a so-called B-zone which (largely) is limited by +3 and -5% as far as frequency is 30 concerned and +/- 8% as far as voltage is concerned.

For conventional electric generators with dc-magnetized poles, as stated above, a given and fixed ratio exists between the frequency of the generated voltage and the 35 speed of rotation of the rotor at a given pole number. Connecting an electric generator to a stiff power network where the synchronous speed/frequency of the electric

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generator deviates from the frequency of the network implies significantly increased losses in the electric generator. Now, if a normally working 50 Hz power network for various reasons maintains a 2% lower frequency, a

5 connected electric generator will still work with a synchronous frequency if the speed of rotation of the rotor is 2% lower than nominal speed. Even if in this way, under certain circumstances, synchronous conditions may be obtained, a varying speed of a connected electric

10 generator entails considerable problems, especially as it may be difficult enough to allow the speed variations to be as large as a technically-economically desirable range of deviation +/- 10%.

15 To solve the above problems, the frequency control of electric generators with varying speed of rotation has had to be solved in other ways. For this purpose, various embodiments are available according to the state of the art, some of which will be described in the following.

20 In principle, one of the simplest ways of achieving the correct frequency for connecting an electric generator to the electrical network, where the speed of the generator varies within the above-mentioned limits, is to connect

25 between the generator and the power network an ac-to-ac converter according to Figure 1c. From an economical point of view, however, this is a very doubtful embodiment since the ac-to-ac converter must be designed for full power.

30 The embodiments which have been used, according to the state of the art, are, however, substantially based on another principle known for such machines within electrical engineering (see, e.g., the article in Hitachi

35 Review mentioned below). The principle will be exemplified here by means of an example of numerals based on an electric generator which is to generate a voltage of the

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frequency 50 Hz. A typical hydroelectric plant is dimensioned for a basic speed of 375 r/min and consequently has 16 poles according to equation (1). If the unit for certain reasons is driven by the turbine to rotate at 360 r/min, the synchronous frequency of the electric generator, upon dc excitation of the rotor poles, according to equation (1), would generate a voltage of the frequency 48 Hz.

If the rotor winding is designed as an ac winding and this winding is supplied with a voltage with the difference frequency between the synchronous frequency  $f_r$  at 360 r/min and the desired frequency 50 Hz, that is, with  $f_c=2$  Hz, the frequency of the electric generator will be  $f_s=50$  Hz. Generally, equation (1) is converted into

$$n_r = (2/p) \cdot (f_s + f_c) \cdot 60 \quad (2)$$

where  $f_c$  is the difference frequency in question. The task of a system for maintaining the frequency of the electric generator constant is thus to ensure that, independently of the actual speed of the drive means, the rotor winding is supplied with a voltage with the actual difference frequency, both as regards subsynchronous and supersynchronous operation. This principle is applied in different ways or with different embodiments. Typical of known embodiments is that the rotor connections take place via three-phase slip rings which transmit the entire shaft power or a large part of the same.

US 5,742,515, "Asynchronous conversion method and apparatus for use with variable speed turbine hydroelectric generation", describes a hydroelectric power-generating system which generates electric power to a power network. In summary, the electricity-generating part of the system may be described on the basis of

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Figure 5 where the parts included are drawn with the same figure symbols and reference numerals as in Figures 2 - 4. According to claim 19 of the US patent, the system comprises (to clarify the reference to the US patent, the terms hydro-/turbine, generator, machine, etc. are used) "a water-driven hydroturbine 6 with a hydroelectric generator 1 for generating hydroelectric power and a rotating converter 11 connected to the hydromachine for transmitting the electric power of the hydromachine to the power network. The rotating converter comprises a rotor winding 12 and a stator winding 13 of which the rotor winding or the stator winding is connected to the hydroturbine unit and the other, via a transformer 8, to the high-voltage power network....." Otherwise, the description discloses that the hydroelectric generator 1 comprises a shaft 2 which is arranged with the rotor of the hydroelectric generator with a winding 3 and the rotating ac winding 4 of an exciter. It is not clear from the figures or the text in the patent whether the "exciter power supply" (Fig. 1A, 62) is a converter rotating with the shaft or if the dc excitation takes place via a stationary converter and transmission via two slip rings. In principle, these are equivalent solutions, but for comparison with the other embodiments, Figure 5 describes that the magnetization takes place via a converter 5 rotating with the shaft. Figure 5 also shows the stationary field winding 9 of the exciter and the stator winding 7 of the hydroelectric generator. As will be clear, this part of Figure 5 is identical with Figure 2.

In other respects, the description shows that, in accordance with Figure 5, the stator power of the hydroelectric generator is transmitted via slip rings 14 on the rotating converter 11 to the rotor winding 12 thereof.

The voltage induced in the stator winding 13 of the converter is connected via a transformer 8 to the power network. Thus, the task of the converter 11 is to provide



the system with the difference frequency which is necessary for the system to be able to deliver a voltage of the proper frequency to the power network at varying speed of the hydroelectric machine. In practice, this implies that, if the hydroelectric machine rotates with its synchronous speed, the converter will be stationary, that is, operate as a stationary transformer. Depending on the actual speed of the hydroelectric machine, the rotor of the converter will thus need a drive source M/G 15 in the form of a motor or a generator with an ac-to-ac converter 16. It may thus be determined that the converter 11 must be dimensioned for largely the same power as the hydroelectric generator and that the slip rings must be able to transmit the full power. The converter 11 rotates with the low difference frequency, which implies that the converter must have forced cooling with a large power loss.

The voltage control of a hydroelectric generator 1 according to the US patent document takes place via the above-mentioned dc excitation. The rotating converter 11 has in its rotor winding 12 and in its stator winding 13 leakage reactances which consume reactive power and cause voltage drops. This may be compensated for with increased dc excitation in the rotor winding 3 of the generator or may, according to the application EP 0749190 A2, associated with the US patent, be compensated for by series capacitors. From the EP application it is also clear that a typical rated voltage for the slip rings is 15 kV. The rated current for such a 100 MVA machine is thus about 4 kA and for a 300 MVA machine it is 12 kA. A significant problem with such machines is consequently to manufacture, utilize and maintain slip rings for these voltages and currents.

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ABB Review 3/1996, pp 33 - 38 discloses an installation where "ABB Varspeed generator boosts efficiency and ope-

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rating flexibility of hydropower plant". The optimization takes place by allowing the turbine and the electric generator to run at variable speed. To still be able to connect the electric generator to a power network with a given and substantially fixed frequency, the frequency of the electric generator is adapted to the mains frequency with the aid of a so-called subsynchronous/supersynchronous converter cascade. To be able to compare this generator drive more easily with the other embodiments described, the relevant part of Figure 4 in the ABB publication has been reproduced in Figure 6 and drawn with the same figure symbols and reference numerals as in Figures 2-4 in the above-mentioned patent document. Thus, it comprises a water-driven turbine 6 with an electric generator 1 (G2) for generating hydroelectric power. The electric generator 1 comprises a shaft 2 which is arranged with the rotor of the hydroelectric generator with the winding 3. Figure 6 also shows the stator winding 7 of the electric generator. The frequency adaptation to the actual mains frequency takes place with the aid of the subsynchronous/supersynchronous converter cascade 17 (CC), which in actual fact is a so-called cycloconverter/frequency converter. The feeding to the network side thereof takes place via a transformer 18 (TR) and the actual difference frequency is fed into the rotor winding 3 of the electric generator via slip rings 19. Thus, the voltage generated with the correct frequency is then fed via a transformer 8 to the power network. Such a frequency adaptation of an electric generator, which is driven by a variable speed, is a so-called Static Scherbius drive (see below under the description of the background art as regards motor drives).

To be able to achieve the correct difference frequency continuously and under varying operating conditions, a frequency control system is required. In that embodiment

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of the background art which is shown in Figure 5, the frequency control system is to ensure that the rotor of the converter rotates at the correct speed with the aid of a control signal 16a to the control device of M/G, and in the example shown in Figure 6 the frequency control system shall provide the correct control signal 17a to the ac-to-ac converter 17. However, the frequency control systems are outside the scope of this invention and thus will not be described in more detail.

For connection to a power network, a voltage control with respect to amplitude and phase angle is also required in addition to some form of frequency control. In the same way as above, the voltage control systems are outside the scope of this invention.

Depending on the actual frequency range both as regards frequency and voltage, in slip-ring ac machines, power will circulate internally via the circuit comprising stator, rotor, slip rings, transformer and converter. The power dimensioning of these parts is also outside the scope of this invention, although a relative comparison between different embodiments will be described under the summary of the invention to demonstrate the advantages possessed by embodiments according to the invention in relation to the prior art.

SU 1746474 A1 describes an "Asynchronised Synchronous Machine having Reversible Excitation System". This is an electric machine with a conventional three-phase stator winding connected to a power network. The rotor is provided with galvanically separated phase windings. Each one of these is connected to a respective double converter rotating with the shaft. These converters are designed with thyristors and are supplied from a magnetizing exciter rotating with the shaft. Thus, the converters are machine-commutated from the magnetizing exciter and are

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arranged such that they may provide the respective rotor winding with alternating voltage with a frequency corresponding to the slip frequency of the machine. It is obvious that there are problems when changing current direction in the rotor windings. To ensure the transition and to avoid large short-circuit currents when the magnetization current is to change direction, it has been necessary to resort to a special connection arrangement for the connection of the double converters. This consists of each rotor winding being provided with an extra terminal a number of winding turns from each end terminal.

To be able to adapt the frequency of the electric generator of a wind-power plant to the frequency of a connected power network at varying wind speed, there is a brushless system, OPTI-SLIP®, produced by Vestas Danish Wind Technology A/S, Denmark, described in an article "Semi-variable speed operation-a compromise?", presented in the Proceedings of 17th Annual Conference, British Wind Energy Association, 19-21 July 1995, Warwick, UK. The principle of the control is based on the well-known method involving loss control with the aid of varying external rotor resistors connected via slip rings to the rotor winding of the electric generator. Contrary to the well-known slip-ring method, the OPTI-SLIP® plant is arranged with an ac-dc-dc converter rotating with the shaft and a fixed rotor resistor rotating with the shaft, directly connected to the rotor winding. The ac-to-dc converter is designed with a diode rectifier, which in turn is short-circuited by a dc-to-dc converter. The speed control of the wind-power plant takes place via an internal rotor-current control. The loss power associated with the control is thus developed in the rotor resistor rotating with the shaft and is then emitted into the surrounding air. It is clear from the conference article that the speed may be up to 4% above the synchronous

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speed, resulting in power losses of the same percentage as the losses in the rotor circuit.

Start-up of electric generators to the actual control  
5 range takes place in the same way as for constant-speed generators, that is, the turbine accelerates the electric generator up to the range of possible synchronization.

The immediately following part of the background art  
10 deals with the use of ac machines as motors with varying speed with a more or less limited speed range around a synchronous speed determined by the frequency of the ac network and the pole number of the main machine according to equation (1).

15 Variable-speed-controlled motor drives have existed for about 100 years. The very first ones were so-called Ward-Leonard drives, that is, dc motor drives. Somewhat later, various motor drives based on ac machines emerged. These  
20 motor drives are often named after their inventors Kramer, Scherbius, Schrage, et al. Characteristic of these machines is that they are provided with a wound rotor as well as brushes and slip rings or a commutator. Typical is also that they are arranged to return electric  
25 power from the rotating parts to stationary parts of the installation as, for example, rotor resistors, or that they are controlled with machines as actuators.

After the introduction of the converters, the interest in  
30 speed-controlled motor drives with ac machines has generally increased again. Recent years' research has focused on the speed control of so-called "brushless ac machines" via substantially two principles, namely, by varying the stator frequency with ac-to-ac converters, so-called  
35 stator converters for full power, and during the last few decades often by so-called field-vector control, that is, division into flow and torque-forming currents.

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The introduction of converters has also resulted in the classical Kramer and Scherbius drives, which follow equation (2), receiving renewed interest, and these are nowadays often referred to as "Static Kramer" and "Static Scherbius", respectively. The renewed interest primarily relates to motor drives with powers in the MW class. It is these motor drives that are to be regarded as the closest prior art relative to the present invention. These are described in a large number of documents, inter alia summarized in IEE Proc, Vol. 131, Pt. A, No. 7, September 1984, pp 535-536, "Electrical variable-speed drives", by B. L. Jones et al.

A static Kramer drive is often referred to as a sub-synchronous converter cascade and has a connection, the principle of which is shown in Figure 7. The stator winding 20 of the horizontal-shaft motor is connected to a power network. The rotor winding 21 is connected, via slip rings 22, to a rectifier 23, the voltage of which becomes proportional to the slip. This voltage is connected in inverse feedback by the voltage from an inverter 25 connected to the same power network via a transformer 24. The voltage of the inverter is a trigonometric function of its control angle and in this way determines the speed of the motor. In this way, in a static Kramer drive, the slip power is fed back to the network by frequency conversion in two stages via an intermediate dc link.

As regards a drive according to Figure 7, power may be transmitted in one direction only via a rectifier, but in both directions if the rectifier 23 is designed as a converter with thyristors. To change the direction of rotation, the phase sequence of the motor connection need to be shifted.

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A static Kramer drive may be characterized as a current-controlled motor drive.

5 A static Scherbius drive is clear from Figure 8. The stator winding 20 of the motor is connected to a power network in the same way as in Figure 7. The rotor winding 21 is connected, via slip rings 22, to a cycloconverter/-frequency converter 26 connected to the power network via a transformer 24. Specific for a Scherbius drive is that  
10 the speed is controlled via the rotor connection with the voltage of the cycloconverter, the amplitude, phase and frequency of which may be changed independently of each other. For the control, a feedback from the motor is needed to maintain the correct frequency as well as the  
15 amplitude quotient and the phase ratio between the rotor voltage and the control voltage.

One advantage of the Scherbius drive relative to the Kramer drive is that the frequency converter may supply  
20 the machine with a rotor current also during synchronous operation, which implies that the operation may, without extra electronics, change from subsynchronous to supersynchronous operation. In addition, since the frequency converter is regenerative, a Scherbius drive may brake  
25 both at subsynchronous and supersynchronous speed. It may also continuously operate during synchronous operation without the power semiconductors being overloaded. However, the slip rings may become unsymmetrically loaded with a certain risk of overheating when the operation is  
30 synchronous.

A static Scherbius drive may be characterized as a frequency- and voltage-controlled motor drive.

35 Hitachi Review, Vol. 44 (1995), No. 1, pp 55 - 62 describes an "400-MW Adjustable-Speed Pumped-Storage Hydraulic Power Plant" based on the Scherbius principle,

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- where the vertical-shaft speed-controlled ac machine is used as a pump motor at night and as electric generator in the daytime. Apart from the direction of mounting of the shaft, the fundamental design, connection and functional description of the ac machine are thus the same as for Figures 6 and 8. Interesting numbers in this context are that, in generator operation, the rated power is 395 MVA in a speed range of 330 - 354 r/min and, in motor operation, the rated power is 380 MW in a speed control range of 330 - 390 r/min. The power of the necessary cycloconverter for these control ranges is 72 MVA, that is, it is between 18 and 22% of the respective rated powers.
- 15 The described designs with slip rings and converters both as regards electric-generator and motor drives suffer from certain drawbacks/problems which the invention intends to largely eliminate or reduce.
- 20 The greatest drawback of these drives, and which causes the most problems and faults, are the slip rings and their connections, brushes, etc. These parts of an ac drive are those which have the shortest life and require most maintenance, especially as they are to transmit
- 25 considerable powers (cf., e.g., the designs according to US 5,742,515, where the entire machine power is to be transmitted via the slip rings.)

- In slip-ring ac machine drives, power circulates internally both in the stator circuit, the rotor circuit and the air gap and via the external transformer and the ac-to-ac converter. The circulating power may be both active and reactive. The reactive power is consumed internally in the transformer, in the converter as well as in the
- 35 rotor and stator of the ac machine. This increases the rated nominal power of the electromagnetic circuit, that is, the dimensioning product of rated voltage during no-

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load operation and rated current at full load. At the same time, this also implies that the rated nominal power of the converters is greater than what is needed because of the circulating reactive power.

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For various reasons, the ac motor drives at present have a practical upper limit of about 25 MW. This is substantially due to the problems which arise in connection with starting and accelerating the motor drives on relatively weak power networks. If a synchronous machine were to be started with a direct start, that is, with direct connection into the power network without any attempts to reduce the rotor currents, the starting current could amount to 3 - 6 times the rated current and the starting losses would substantially be developed in the rotating parts where, during the starting/acceleration process, they would be stored adiabatically. In order for a start to take place in a more controlled way, different methods are employed, such as series/parallel connection of the stator windings, with the aid of a starting transformer or with a series reactor or resistor. Start of slip-ring ac machines may take place with full stator voltage with a rotor resistance  $R_s$  which is connected to the rotor winding via the slip rings and which is successively reduced when the machine starts. Such a starting device is shown in Figure 9.

Braking or deceleration of ac machines from the control range around synchronous speed to a standstill according to the prior art is performed in a manner well-known to the person skilled in the art. Braking is a transient phenomenon and in the same way as starting it is associated with changes in the kinetic energy of the rotating system. The simplest electrical method of braking is the so-called counter-current braking, which occurs by changing two phases in the ac voltage connected to the stator winding. The change of kinetic energy associated with the

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transient phenomenon causes loss energy in the rotor circuit, which is therefore classically designed with slip rings and external rotor resistors to carry away the loss energy from the interior of the ac machine in the same way as during starting.

#### SUMMARY OF THE INVENTION, ADVANTAGES

As mentioned in the introduction, the invention comprises an electric rotating ac machine, which in its basic design comprises a main machine and a regulating machine with a common mechanical shaft and a converter rotating with the shaft. The invention also relates to a method when using the converter rotating with the shaft.

Characteristic of the main machine is that it is designed with ac windings in both stator and rotor and that it may operate both as an electric generator and as a motor.

The regulating machine has several functions. It is to supply the rotor winding of the main machine with control power/frequency for the actual control range and it is also intended to function as a starting motor for the constant-frequency machine or to transmit the starting losses of the main machine to external resistors.

The converter also has several functions. Its main task is to function, during operation, as an ac-to-ac converter according to the previous definition. During starting, it should be able to function as an ac poly-phase coupler or as an ac phase-angle/voltage regulator or as an ac short-circuit coupler for the rotor winding of the regulating machine. During controlled braking and/or stopping, the converter is to be able to function as an ac phase-angle/voltage regulator or as an ac poly-phase coupler. The invention also comprises a method for

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use of the converter rotating with the shaft in accordance with the above.

5 However, the installation designs when the machine is operating as an electric generator and as a motor, respectively, differ somewhat from each other primarily as regards rated powers, rated voltages and starting methods. In certain contexts, however, the machine may be used both as an electric generator and as a motor.

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Initially, the summary of the invention will deal with the design of the stator winding of the main machine, which is largely common to the machine both as an electric generator and as a motor. Then follows a  
15 description of the machine when it is used as an electric generator with a variable speed and when it is used as a motor with variable speed. Thereafter, the design of the regulating machine and also, to a certain extent, the design of the ac-to-ac converter will be described in  
20 broad outline. Finally, the advantages possessed by a machine according to the invention in relation to the prior art will be described.

It has been generally described above that the stator  
25 winding of the main machine is connected to a transmission and distribution network with medium or high voltage. As shown in the accompanying drawings, the connection may also be transformerless or take place via power transformers. The connection may also take place  
30 vis-à-vis converters for frequency conversion, for power factor correction, for filtering of harmonics, etc.

For direct connection to a high-voltage network, the stator winding of a machine according to the invention is  
35 wound with a high-voltage cable. A preferred embodiment of the cable comprises a current-carrying conductor comprising transposed, both uninsulated and insulated,

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strands. Around the conductor is an inner semiconductive layer which is surrounded by at least one extruded insulating layer which, in turn, is surrounded by an outer semiconductive layer. To avoid induced currents and losses associated therewith in the outer semiconductive layer, this layer is divided into a number of cut-off parts. Each one of these cut-off parts is then connected to ground, whereby the outer semiconductive layer will be located at ground potential or at least near ground potential. This implies that no large randomly distributed field concentrations, varying with the conductor geometry, may arise in the stator winding of the machine. A more detailed description of such a cable and winding as well as the advantages afforded by such a cable and winding in rotating machines is given in WO 97/45919.

As mentioned above, the description of the invention will first deal with how the machine is used as an electric generator with varying speed. One example of the basic design is shown in Figure 10 which, as far as generated voltage is concerned, relates to a conventional electric generator, that is, an electric generator intended for voltages up to 25 kV. To be able to compare the invention in a simple manner with the described background art, Figure 10 has, as far as possible, the same figure symbols and reference numerals as the figures described earlier. There are thus one main machine/electric generator 1, one regulating machine 27 arranged on a common shaft, and one converter 28 in the form of an ac-to-ac converter mounted on the shaft. Otherwise, Figure 10 shows that the ac rotor winding 29 of the regulating machine is connected to the "network side" of the ac-to-ac converter and that its output is connected to the ac rotor winding 3 of the electric generator. The stator winding 30 of the regulating machine may, in the same way as for previously described brushless exciters, be designed with salient poles. As will be clear from the

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following description, also a different embodiment may be used. The main machine/the electric generator and the regulating machine are driven in the manner previously described via a turbine 6. The voltage generated by the electric generator in the stator winding 7 is connected, as above, via a step-up transformer 8 to a high-voltage power network.

The principle of the frequency control at varying speed of the drive means is the same as previously described, that is, the ac rotor winding 3 of the electric generator is supplied with a voltage with the difference frequency which is needed to obtain the desired frequency of the generated stator voltage at the actual speed. The control signal 28a of the frequency control system to the rotating ac-to-ac converter may be created in different ways which are outside the scope of this invention. The same applies to the voltage control of the system as far as amplitude and phase angle are concerned.

It should be noted that when the electric generator is run at a speed which, with a given pole number, corresponds to synchronization to the frequency of the power network, the connection of the ac-to-ac converter to the rotor winding will occur with the frequency zero, that is, with direct current.

Contrary to the state of the art with slip-ring transmission of power/difference frequency to the rotor winding and contrary to the special connection of the rotor winding with galvanically separated windings with extra terminals which are needed with the machine-commutated double converter as described in SU 1746474 A1, according to the invention transmission of power/difference frequency is made to a conventional rotor winding which is connected to a self-commutated double converter which in a preferred embodiment consists



of a matrix converter. Since it is now a question of power transmission to/from the power network, the regulating machine and the converter must be dimensioned for the actual control range both as regards torque and speed and also as regards so-called commutating overlaps because of a "weak-network" nature of the rotating windings. As example of such dimensioning, there is mentioned the power of the cycloconverter relative to the rated power in the Hitachi case. To illustrate this, the regulating machine 27 has been drawn more proportionally correct relative to the power of the electric generator, in contrast to Figures 2, 3 etc., where the exciter shall only supply the electric generator with dc excitation power.

Problems in connection with the commutation of converters may be reduced in various ways. ABB Review 2/97, pp 25-33 describes one method with "Capacitor commuted convertors for HVDC systems". The article describes how the commutating margin is improved and how the reactive power need drops with series capacitors in ac connection, that is, between the line-commutated converter and its transformer, when the converter operates in inverter mode. A corresponding technique is used in connection with the description and embodiments of the ac-to-ac converter integrated into the invention.

The constant-frequency machine with a variable speed according to the invention may, of course, be designed for adaptation to different generating application alternatives. This is particularly true of the winding designs of both the main machine and the regulating machine and hence also of the design of the ac-to-ac converter. As examples of alternative embodiments when it comes to the stator winding of the electric generator, it may also, in addition to the embodiment shown in Figure 10 for a "conventional" high-voltage level as far as elec-

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tric generators are concerned, be designed as the electric generator described in WO 97/45919 for higher voltages according to Figure 11a which is a correspondence to Figure 3. Figure 11b shows an axial end view of a sector/pole pitch of a main machine according to the invention and will be described in greater detail under the description of embodiments. The correspondence to Figure 4, that is, where the electric generator is designed as a high-voltage generator according to WO 97/45907 with 2x3-phase stator windings for supplying an HVDC installation with a 12-pulse voltage, is also a design which is currently of great interest.

Run-up/starting of the constant-frequency machine to the actual control range for operation as an electric generator occurs by the turbine accelerating the main machine and the regulating machine until the machine is capable of assuming the control itself.

An ac machine according to the invention also has a large field of application when it comes to motor drives with varying speed. A basic design for motor drives will be described starting from Figure 12.

In the same way as described for the embodiment with the basic design of the electric generator, also in this case, for comparing the invention with the background art described, to the greatest possible extent the same figure symbols and reference numerals will be used as in the previously described figures regarding motor drives, that is, Figures 7 and 8. Thus, according to Figure 12, there are a main machine/electric motor 1 with a stator winding 20 and a rotor winding 21, a regulating machine 27 arranged on a common shaft and a converter 28 in the form of an ac-to-ac converter. The regulating machine is provided with a rotor winding 29 and a stator winding 30. Otherwise, as is clear from Figure 12, the rotor winding

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29 of the regulating machine is connected to the "network side" of the ac-to-ac converter and its output is connected to the ac rotor winding 21 of the main machine/electric motor. The stator machine 30 of the regulating machine 30 may be designed, in the same way as the brushless exciters mentioned above, with salient poles but also in this case other embodiments may occur. The electric motor and the regulating machine jointly drive the mechanical load (not shown).

The principle of varying the speed of motor drives during ac supply with a "constant" mains frequency is the same as has been described previously for electric generators, that is, that according to Figure 12 the ac rotor winding 21 of the main machine is supplied with a voltage with the difference frequency needed for the m.m.f. and flux waves created by the currents in the stator winding 20 and the rotor winding 29 to rotate synchronously in the air gap of the electric motor 1. The control signal 28a of the speed/frequency control system may be created in different ways. It depends on the requirements for dynamics, power factor, the level of the mains voltage relative to its nominal, etc. In the same way as for synchronous operation of the electric generator as described above, the current in the rotor winding 21 of the electric motor will have the frequency zero during synchronous operation, that is, again there will be a special case with direct current in the ac rotor winding of the main machine.

In the description of the invention both as regards generator and motor operation, it was stated that the rotor winding of the regulating machine is to be an ac winding and that the stator winding may be designed with salient poles but that other embodiments may also occur, depending on different applications. The part of the

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description that follows next will describe alternative embodiments.

The regulating machine creates a local ac network to which only the ac-to-ac converter is connected. The number of poles thereof may thus be chosen relatively freely. To keep its physical dimensions as small as possible for a given speed variation, the regulating machine is preferably designed with more poles than the main machine.

The design with salient poles may also be carried out in different ways. The preferred embodiment consists of "salient poles" with a dc winding. This creates a stationary air-gap flow in the regulating machine which permits a control possibility which is attractive from the installation engineering point of view by varying the magnitude of the air-gap flow via the value of the direct current. The design with salient poles in the stator of the regulating machine also comprises the air-gap flow being created by permanent magnets, which, however, implies a largely constant air-gap flow. The design with salient poles of the stator of the regulating machine is primarily of interest when the invention is to be used with different generator drives.

The stator winding of the regulating machine may also be designed as an ac winding, whereby a rotating air-gap flow is created in the regulating machine. Such a design primarily permits supply of excitation output during operation, combined, however, with certain input/output of shaft power. This may be eliminated by supplying direct current into part of, or by switching of, the ac winding. Another considerable advantage of an ac winding in the stator is that the starting conditions are significantly improved when using the machine according to the invention as a motor.

[illegible]

Ac machine drives according to the invention have a considerable number of advantages as compared with  
35 corresponding drives designed according to prior art:

- Brushless control of the ac machine is performed.

- Since, in these brushless ac machines, no power circulates around via the stator circuit, this means an approximate halving of the necessary converter ratings.
- An ac machine according to the invention may be used, both as motor and as generator, for generating reactive power to the power network or at least they do not withdraw any reactive power from the machine.
- Power electronic converters reduce the losses and physical dimension of the main circuits.
- Since neither active nor reactive circulating power loads the winding of the stator, also the losses will significantly decrease relative to those of the prior art.
- The rotor windings of both the main machine and the regulating machine may be designed with lower and hence less expensive voltage levels, since there are no longer any limiting external criteria imposed by slip rings, extended busbars and cabling.
- Harmonics in the converter circuits essentially remain inside the rotating machine and thus do not propagate to the power network.
- The machine may be designed for one, two or more high-power connections to a power-supply network.

To further describe the advantages of a constant-frequency machine with a varying/variable speed according to the invention, the following table shows a relative power comparison based on a given apparent rated power  $S_n$  for the embodiments described. The comparison relates to

the sum power for the rotating machines, ROT, the sum power for the transformers included, TRAFO, the sum power for the converters included, SR, the sum of the power transmitted via slip rings, SL, and output power, UE.

- 5 (T.S.) and (U.F.), respectively, mean that the figure belongs to the prior art or to the invention.

Machine according to		ROT	TRAFO	SR	SL	UE
Figure 2	(T.S.)	$S_n$	$S_n$	$0.05 S_n$	0	$S_n$
10 Figure 3	(T.S.)	$S_n$	0	$0.05 S_n$	0	$S_n$
Figure 5	(T.S.)	$2.2 S_n$	$S_n$	$0.2 S_n$	$1.15 S_n$	$1.1 S_n$
Figure 6	(T.S.)	$1.3 S_n$	$1.4 S_n$	$0.4 S_n$	$0.4 S_n$	$1.1 S_n$
Figure 9	(U.F.)	$1.3 S_n$	$S_n$	$0.3 S_n$	0	$1.1 S_n$
Figure 10	(U.F.)	$1.3 S_n$	0	$0.3 S_n$	0	$1.1 S_n$

15

A machine according to Figure 2:

All the "major" manufacturers of electric generators are capable of manufacturing constant-speed machines with full-power step-up transformers with brushless exciters.

- 20 In an installation according to the figure, the electric-power generator 1 and the step-up transformer 8 are designed for the same apparent rated power  $S_n$ .

The standard concept for an installation is to use, for the brushless design, an exciter, rotating with the

- 25 shaft, with a converter/ac-to-dc converter 5 for supplying the field winding 3 in the rotor. The rated nominal power of the converter is to some extent dependent on the dynamic requirements of the voltage control. Typical values are, however, that it is
- 30 dimensioned for 5% of the power of the electric generator. The machine has no slip rings for transmission of the dc excitation to the field winding.

A machine according to Figure 3:

- 35 This is a machine according to the previously described WO 97/45919, that is, an electric generator 1 for high voltage in which the installation does not need any step-up transformer. The rated nominal power of the converter

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rotating with the shaft is as above, that is, about 5% of the apparent rated power. The magnetization may take place without slip rings.

5 A machine/Machines according to Figure 5:

An estimation of the sum of the apparent rated power for the rotating machines shows that it is about  $2.2 \cdot S_n$ .

Without specifying the basis of this assessment in more detail, it may be determined that, since the

10 machine/converter 11 shall have the rated power  $S_n$ , as well as the transformer 8, the machine 1 must be designed for the same power plus the reactive power consumed by the machine 11. The sum of the power of the rotating machines must, in addition thereto, comprise the power  
15 required for driving the machine 15, that is, the drive source of the converter.

The sum converter power for the ac-to-ac converter 16 and for dc excitation of the machine 1 is estimated at about

20  $0.2 \cdot S_n$ .

The total power through the slip rings is the apparent power, transmitted from machine 1 to machine 11, which is estimated at about  $1.15 \cdot S_n$ , starting from a short-

25 circuit reactance of machine 11 of 0.15 pu. The series capacitors mentioned in EP 0749190 will also have the value 0.15 pu. As previously described, very high demands are placed on the power-transmission capacity of the slip rings.

30

A machine according to Figure 6:

As previously described, this is a system based on the Scherbius cascade, where the rotating electric machine/electric generator 1 is assumed to be designed

35 with slip rings 19 to the cascade. The ac-to-ac converter 17, that is, the converter in the cascade, is dimensioned for the actual control range and for the reactive power

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it consumes. The installed rated power for the converter may thus be estimated at about  $0.4 \cdot S_n$ , which also corresponds to the total power through the slip rings. The apparent rated power of the rotating machine will consequently be about  $1.3 \cdot S_n$  and the total installed rated power for the transformers will be about  $1.4 \cdot S_n$ .

Machines according to Figures 10, 11a and 11b:  
These figures represent a machine according to the present invention, that is, "A constant-frequency machine with a varying/variable speed". To sum up, the machine comprises a first electric machine 1 called main machine and a second electric machine 27 called regulating machine with a common mechanical shaft 2 and a converter/ac-to-ac converter 28 rotating with the shaft. According to Figure 10, the main machine 1 may be designed with high voltage "conventional" to electric generators, that is, up to 25 kV and a step-up transformer 8 or it may, according to Figure 11a, be designed with a high-voltage winding, in which case the step-up transformer is eliminated. Since reactive power does not circulate internally via the stator of the main machine, the rated nominal power for the ac-to-ac converter for the same control range as for the machine according to Figure 6 will be smaller, approximately  $0.3 \cdot S_n$ . The rated power of the regulating machine is consequently also  $0.3 \cdot S_n$ , and the total apparent rated power of the rotating machine is  $1.3 \cdot S_n$ . The rated power of the transformer 8 in Figure 10 is  $1.0 \cdot S_n$ . Machines according to the invention thus comprise no slip rings.

A constant-frequency machine according to the invention, in contrast to the embodiments described under the background art, has an advantage which significantly improves the starting and acceleration conditions. It has been described before that the stator winding of the regulating machine may be formed as an ac winding to allow the supply of magnetizing power for the regulating machine during

operation, for example by means of an auxiliary winding in the stator of the main machine. It is also indicated in that connection that an ac winding in the stator of the regulating machine improves the starting conditions when the constant-frequency machine is used as a motor. If the stator winding of the regulating winding is designed as a three-phase winding, an external variable resistor may be connected, during the starting operation, to the connections of the winding to control the magnitude of the starting current and to a substantially resistive phase angle as well as to carry away losses in the main machine which are associated with the starting operation. This may be done by connecting the converter as an ac polyphase coupler. In principle, starting may also occur in such a way that the stator winding of the regulating machine is connected directly to a power network and that the rotor windings of the regulating machine and the main machine are connected together, via the converter, and that an external variable resistor is connected to the stator winding of the main machine. By controlling the converter, rotating with the shaft, as an ac phase-angle/voltage regulator during the starting operation, the external resistor may be a fixed resistor. Both the main machine and the regulating machine operate in such connections as rotating transformers. A more detailed description of start-up arrangements will be given under the description of the preferred embodiments.

For a normal speed-control range and a normal capacity as regards reactive power of the constant-frequency machine, the regulating machine is dimensioned for about 30% of the power of the main machine. This permits a possibility to use the regulating machine as a starting motor during start-up, the stator winding thereof being supplied from a separate frequency converter. One condition is then that the converter rotating with the shaft is connected as an

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5 These alternative starting methods imply that the upper  
power limit to motor drives during start-up on weak power  
networks may be increased to at least 40 MW.

From a technical point of view, the stator and rotor  
10 windings of the main machine with the respective stator  
and rotor cores operate as a unit which

- ◆ creates torque and rotating motion
- 15 ◆ adapts the incoming high/medium voltage to a medium/low voltage which is optimal for the ac-to-ac converter, rotating with the shaft, as well as the regulating machine
- 20 ◆ forms a "step-down" power transformer between the power supply network and the power electronics
- ◆ with a high-voltage cable in the stator, may have a transformation ratio between the stator voltage and the
- 25 rotor voltage which may amount to 100-300 times without capacitively caused amplifications of high-frequency voltages from/to the electric power system or the auxiliary-power winding arising
- 30 ◆ with the windings and cores of the main machine, filters the sub-harmonics/harmonics in current, which are generated in the ac-to-ac converter and are directed towards the main machine, thus preventing these from being transmitted to the electric power
- 35 system via the stator winding of the main machine.

From a technical point of view, the stator and rotor windings of the regulating machine with the respective stator and rotor cores operate as a unit which

- 5     ♦ with a suitable choice of the number of poles, creates a higher frequency, 50 - 150 Hz, than the power supply network, and thus
- 10    ♦ during normal operation, provides conditions for a good sinusoidal shape of the rotor current of the main machine generated via the ac-to-ac converter
- 15    ♦ with the windings and cores of the regulating machine, during normal operation filters the sub-harmonics/-harmonics, which are generated in the ac-to-ac converter and which are directed towards the regulating machine, thus preventing these from being transmitted via the stator winding of the regulating machine and the auxiliary-voltage winding of the main machine to  
20    the electric power system and, via the stator winding of the regulating machine, to an external supply source, respectively
- 25    ♦ during transient phenomena, such as starting and controlled braking and stopping, functions as a "rotating transformer" which conducts the losses associated therewith from the rotating parts of the machine to an external resistor.
- 30    A description of the technical functions of the converter, rotating with the shaft, will be given under the description of the preferred embodiments.

#### BRIEF DESCRIPTION OF THE DRAWINGS

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Figure 1 shows block diagrams of the converters which occur in the description.

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Figure 2 shows, in principle, how brushless exciters for dc excitation are used in connection with conventional electric generators, that is, with a voltage up to 25 kV.

- 5 Figure 3 shows, in principle, how brushless magnetizing exciters are used in connection with electric generators designed according to WO 97/45919, that is, with even higher voltages.
- 10 Figure 4 shows, in principle, how brushless magnetizing exciters are used in connection with electric generators designed according to WO 97/45907, that is, as a 2x3-phase high-voltage generator for supplying an HVDC installation.
- 15 Figure 5 shows, in principle, the electric-power generating part of an installation which is clear from US 5,742,515, "Asynchronous conversion method and apparatus for use with variable speed turbine hydroelectric generation".
- 20 Figure 6 shows, in principle, the electric-power generating part of an installation which is evident from an article in which "ABB Varspeed generator boosts efficiency and operating flexibility of hydropower plant".
- 25 Figure 7 shows, in principle, how a static Kramer drive is designed.
- 30 Figure 8 shows, in principle, how a static Scherbius drive is designed.
- 35 Figure 9 shows how external rotor resistors are connected to the rotor winding via slip rings during a starting cycle.

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Figure 10 shows a fundamental embodiment of a machine according to the invention, used as an electric generator for conventional high voltage, that is, for voltages up to 25 kV.

5

Figure 11a shows a fundamental embodiment of a machine according to the invention, used as an electric generator designed according to WO 97/45919, that is, with even higher voltages.

10

Figure 11b shows an embodiment of an axial end view of a machine according to the invention, used as an electric generator for high voltage corresponding to machines according to WO 97/45919.

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Figure 12 shows a fundamental embodiment of a machine according to the invention, used as a motor for conventional high voltage, that is, for voltages up to 25 kV.

20

Figure 13 shows a fundamental circuit diagram for the windings of both the main machine and the regulating machine with the converter, rotating with the shaft, in the form of a matrix converter with bidirectional valves.

25

Figure 14 shows an example of alternative bidirectional controllable/extinguishable valves.

30

Figure 15 shows a fundamental circuit diagram for the windings of both the main machine and the regulating machine with the converter, rotating with the shaft, in the form of a voltage-source direct converter with anti-parallel-connected thyristor bridges.

35

Figure 16 shows a fundamental circuit diagram for the windings of both the main machine and the regulating machine as well as an indication of the various functions of the converter rotating with the shaft.

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Figure 17 shows a fundamental circuit diagram for the windings of both the main machine and the regulating machine as well as an indication of the function of the converter, rotating with the shaft, when an external variable resistor is connected to the stator winding of the regulating machine.

Figure 18 shows a fundamental circuit diagram for start-up with an external resistor connected to the stator winding of the regulating machine and with the converter in the form of a matrix converter utilized as an ac polyphase coupler.

Figure 19 shows a fundamental circuit diagram for start-up with an external resistor connected to the stator winding of the regulating machine and with the converter in the form of antiparallel-connected thyristor bridges utilized as an ac polyphase coupler.

Figure 20 shows a start-up arrangement of the main machine with the regulating machine as starting motor, the stator winding of which is supplied from a separate frequency converter.

Figure 21 shows how the stator of the main machine is provided with a winding for auxiliary-voltage supply of the stator of the regulating machine.

#### DESCRIPTION OF PREFERRED EMBODIMENTS

The power electronics included for the main function in the constant-frequency machine according to the invention is to be found in the rotating parts of the machine. Optimum voltage levels in the windings of the rotor circuits are determined, independently of the mains voltage, primarily by the maximum permissible voltage levels of the power semiconductors and the actual

connection and with and without series-connected semi-conductors. As regards the stator winding of the main machine, on the other hand, there are no such limitations. It may therefore be manufactured for direct  
5 connection to high-voltage networks. This is made possible by manufacturing/winding the stator winding with high-voltage cables, inter alia according to WO 97/45919. The laminated magnetic circuit of the stator will therefore first be described based on the use of high-voltage  
10 cables in the stator winding.

An example of an embodiment of an axial end view 31 of a sector/pole pitch of a main machine according to the invention for high voltage is clear from Figure 11b. Each  
15 sector/pole pitch is composed in conventional manner of sector-shaped electric sheets. The stator of the machines will thus consist of a number of sectors/pole pitches which together form a laminated stator core. From a radially outermost ridge portion 32 of the core, a number  
20 of teeth 33 extend radially towards the interior of the rotor. Between the teeth there are a corresponding number of slots 34. The use of the above-mentioned high-voltage cable 35 implies, among other things, that the depth of the slots for high-voltage machines is made larger than  
25 what is required according to the prior art. The slot has a cross section decreasing towards the rotor since the need of cable insulation becomes lower for each winding layer towards the interior of the rotor. As will be clear from the figure, the slot consists substantially of a  
30 circular cross section 36 around each layer of the winding with narrower waist portions 37 between the layers. Such a slot cross section may, with a certain right, be referred to as a "bicycle chain slot". Since a relatively large number of layers will be needed in such  
35 a high-voltage machine and the supply of cable dimensions with regard to insulation and external semiconductors is limited, it may in practice be difficult to achieve a

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desirable continuous decrease of the cable insulation and the stator slot, respectively. In the embodiment shown in Figure 11b, cables with three different dimensions of the cable insulation are used, arranged in three sections 38, 39 and 40, dimensioned accordingly, that is, in practice there will be a modified bicycle chain slot. The figure also shows that the stator tooth may be shaped with a practically constant radial width along the whole depth of the slot. The stator may be provided with a winding 41 for auxiliary-power supply, for example for the stator winding of the regulating machine.

Since also the rotor is provided with an ac winding, its core will consist of a design - with a number of slots somewhat differing from that of the stator - of a number of laminated sectors/pole pitches with rotor slots 42 for the rotor winding 43. The rotor winding is to be supplied from the ac-to-ac converter 44 with a voltage with the actual difference frequency. The voltage dimensioning of the rotor winding will then be substantially determined by the maximum permissible voltage levels in the power semiconductors included in the ac-to-ac converter. This, in turn, will be determining for the design of the rotor winding. It may thus be designed according to the prior art for conventional high/medium voltage machines or, as the one mentioned above, with a high-voltage cable, that is, according to WO 97/45919.

The ac-to-ac converter 44, rotating with the shaft, shown in Figure 11a is to be able to convert the relatively high frequency, 50-150 Hz, of the voltage generated in the rotor winding of the regulating machine to the difference frequency, 0-10 Hz, depending on the control range in question. If the converter is designed with silicon-based power semiconductors/valves with a valve in the branches of the converter, the rotor windings of the main machine and the regulating machine will be dimen-

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5 Dimensioning as regards voltage for the rotor windings of the main machine and the regulating machine will be access to, choice of and connection, i.e. without or with a series connection, of power semiconductors for the ac-to-ac converter.

Figure 13 shows a fundamental circuit diagram for the windings of both the main machine and the regulating machine with the ac-to-ac converter, rotating with the shaft, in the form of a matrix converter with bidirectional valves. In the example shown, the stator winding 45 as well as the rotor winding 46 of the main machine are drawn as Y-connected three-phase windings. The matrix converter 47, with the necessary shunt capacitors for creating a high-frequency low-impedance loop where the current may communicate in a simple manner between the phases in the rotor winding of the regulating machine, is connected between the ac rotor winding of the main machine and the ac rotor winding 48 of the regulating machine. The above-mentioned "commutating overlaps because of a weak-network nature of the rotating windings" are eliminated by means of the matrix converter and its shunt capacitors. The regulating machine may thus be designed for a lower rated nominal power. The stator winding 49 of the regulating machine is shown as a three-phase winding in the embodiment shown.

35 Figure 14a shows a bidirectional valve in the form of two  
GTO thyristors or two IGCTs. Figure 14b shows a bidirec-

tional valve with two IGBTs. Figure 14c shows a bidirectional valve with one IGBT.

Figure 15 shows a fundamental circuit diagram for the  
5 windings of both the main machine and the regulating  
machine with the ac-to-ac converter, rotating with the  
shaft, in the form of a voltage-source direct converter  
with antiparallel-connected thyristor bridges. In the  
10 same way as in Figure 13, both the stator winding 45 and  
the rotor winding 46 of the main machine are drawn as Y-  
connected three-phase windings. The voltage-source direct  
converter with antiparallel-connected thyristors 50 is  
connected between the ac rotor winding of the main  
15 machine and the ac rotor winding 48 of the regulating  
machine. In the same way as for the matrix converter, in  
order to facilitate the commutation, also here capacitors  
may be series- or shunt-connected between the rotor  
winding of the regulating machine and the ac-to-ac con-  
20 verter and between the rotor winding of the main machine  
and the ac-to-ac converter, respectively. They may also  
be connected in series and/or in parallel with internal  
terminals inside the rotor winding of the regulating  
machine. Connection of capacitors in this way implies  
25 that the regulating machine may be designed for lower  
rated nominal power. The stator winding 49 of the regula-  
ting machine is, in the embodiment shown, also here shown  
as a three-phase winding.

As mentioned before, the scope of the invention comprises  
30 a plurality of different alternative embodiments for the  
windings of both the main machine and the regulating  
machine.

As regards the stator winding of the main machine, a  
35 preferred embodiment is a three-phase winding as the one  
shown in Figures 13 and 15, that is, a conventional Y-  
connected winding. When the machine is to be used in an

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winding consists of a three-phase winding, it may, by means of changing-over switching, be used for dc excitation. The design of the stator winding of the regulating machine is often determined by how the machine is to be started from stationary state up to the range of speed in question.

Common to the current applications with the constant-frequency machine is that the load only has a need of a limited control range around the synchronous speed of the main machine.

An ac machine according to the invention has a large number of fields of application as regards motor drives. There are processes with motor drives which, for various reasons, at present do not use speed control but which, with ac machines according to the invention, could be significantly improved.

The stator winding of the machine may be dimensioned for connection to power supply networks with voltage from an established low voltage up to classical high-voltage levels. Determining for the voltage which is to be used in the stator winding are largely the available mains voltage and the frequency range in question.

For motor powers of just a few megawatts, the stator winding is connected preferably to a medium-voltage level of between 1 and 36 kV.

At rated powers of above 10 MW, the connection of the machine to the power supply network may preferably be dimensioned for 50 kV or higher, for example 130 kV, that is, be connected to a transmission and distribution network. By connecting to these mains-voltage levels, above all high current forces and voltage drops in the power network during the starting procedure are avoided.

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- As mentioned in the preamble to the description of the embodiments, the converter rotating with the shaft is switchable for several different functions. In addition to the function as ac-to-ac converter during operation, it may also be connected for several functions in connection with starting and controlled stopping of the constant-frequency machine. Figure 16 shows the preferred embodiment as regards the design of the windings during operation as well as a summary of the functions of the converter 51 both during operation, starting and stopping. Controlled braking and stopping will be described later on. The functions of the converter during controlled operation and starting are as follows:
- 15 ♦ The function 51a of the converter corresponds to its function during operation, that is, as an ac-to-ac converter according to the definition given above.
  - 20 ♦ The function 51b of the converter corresponds to its function during starting as an ac polyphase coupler which electronically interconnects input and output connections for interconnection of the rotor windings of the main machine and the regulating machine when an external variable resistor 52 is connected to the stator winding of the regulating machine according to Figure 17.
  - 30 ♦ The function of the converter 51c corresponds to its functions during starting as an ac phase-angle/voltage regulator between the rotor windings of the main machine and the regulating machine when an external fixed resistor is connected to the stator winding of the regulating machine.
  - 35 ♦ The function 51d of the converter corresponds to its function during starting as an ac short-circuit coupler of the rotor windings of the regulating machine when

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directly connecting the stator winding of the regulating machine to a power network according to Figure 18.

Figure 18 otherwise shows a fundamental circuit diagram for starting the constant-frequency machine by direct connection of the main machine to a power network. Starting occurs in the manner described previously with an external three-phase controllable resistor 52 connected to the three-phase stator winding of the regulating machine. The converter is now connected as an ac polyphase coupler according to 51b which connects each phase connection of the rotor winding of the main machine directly to the corresponding phase connection of the rotor winding of the regulating machine. The starting losses of the main machine are now connected by way of a transformer to the regulating machine which then, via its stator winding, transfers the losses to the external resistors.

The mode of operation of the converter when it is to function as an ac polyphase coupler may be achieved in various ways. Figure 18 shows in detail how the converter is arranged as a polyphase coupler with a matrix converter. This function is obtained by "firing" one valve, the one marked in coarse lines, in each branch. Figure 19 shows the function as an ac polyphase coupler with the converter in the form of antiparallel-connected thyristor bridges 50a and 50b. As will be clear, it is now suitable for the rotor winding of the main machine to comprise 2x3-phase windings 46a and 46b for 6-pulse-connected thyristor bridges where each bridge needs to be provided with a pair of antiparallel-connected thyristors, marked in coarse lines, and with the corresponding rotor windings 48a and 48b of the regulating machine.

For a normal speed range of the constant-frequency machine, the regulating machine is designed for about 30%

of the power of the main machine. This permits a possibility of using the regulating machine during start-up as a starting motor, the stator winding of which is supplied from a separate frequency converter 53, not rotating  
5 along with the shaft. One condition is then that the converter rotating with the shaft is connected as an ac short-circuit coupler, that is, as the function 51d, of the rotor windings of the regulating machine. Such a start-up arrangement with the frequency converter 53 is  
10 shown, in principle, in Figure 20.

Controlled braking from the control range to a standstill is performed with the same main circuits as for starting, that is, as Figures 18 and 19. In that connection, the  
15 converter rotating with the shaft is utilized as

- ♦ an ac polyphase coupler, that is, as 51b above, between the rotor windings of the main machine and the regulating machine for controlling active and reactive power  
20 by direct connection of the windings with and/or without shifting the phase sequence. The operations are performed by so-called counter-current braking and the power development associated with the transient phenomenon occurs in an external variable resistor 52.  
25 In addition, a change of phase sequence must take place in the ac voltage connected to the stator winding of the main machine, or as
- ♦ an ac phase-angle/voltage regulator, that is, as 51c  
30 above, whereby the external resistor is fixed and the control occurs through that proportion of the alternating current of the rotor circuit which is let through. Also in this case, a change of phase sequence must take place in the ac voltage connected to the stator winding  
35 of the main machine, or as

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- ♦ an ac short-circuit coupler, that is, as 51d above, for controlled braking with the aid of a frequency converter 53 in Figure 20. A change of phase sequence for connection to the stator winding of the regulating machine from the frequency converter must occur. The frequency converter must be able to feed back energy to the power network or develop braking energy in an external resistor.
- 10 Figure 21 shows how the stator of the main machine is provided with a winding 54 for auxiliary-voltage supply of the stator of the regulating machine with direct current via a controlled converter 56. During dc excitation of the stator winding of the regulating machine, one of the phase windings must be turned around compared with connection to a three-phase ac network.

One example of a motor drive which could advantageously use a machine according to the invention are so-called refiner drives. According to the state of the art, newsprint paper, for example, is manufactured using constant-speed synchronous motors which are limited to about 25 MW because of the problem of starting towards weak power networks. A motor drive according to the invention could, in addition, entail increased rate of production in existing plants.

Slip-ring static Kramer and Scherbius drives for pumps and fans could advantageously be replaced by machines according to the invention.

Wind-tunnel drives are one example of high-power plants of over 100 MW which are well suited for ac machines according to the invention. These are at present designed as speed-controlled systems with synchronous machines with salient poles and current intermediate-link converters for full power.

The stator winding of the regulating machine may, during operation, be connected to a low-power dc network or to an ac single-phase or three-phase network. These networks may be arranged by utilizing the auxiliary-power winding, mentioned above, in the stator of the main machine. This means that the constant-frequency machine has one single connection to power supply networks, whereby one transformer is saved. If no external resistor is used during the starting operation, the regulating machine may be designed with permanent magnets.

Parallel connection of power semiconductors and parallel connection of converter modules, respectively, for, for example, 2x3-phase windings are to be preferred for operations carried out by machines according to the invention. If the rotor voltage is selected within the range of 1 - 15 kV, that is, if the windings are designed as random-wound coils or form coils, a good fill factor is obtained for the rotor slots of the machines. Still higher rotor voltages of up to several tens of kV, that is, for machines according to WO 97/45919, may come into question when the power semiconductors for the ac-to-ac converter reach such levels.

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